10/525927

PCT IT 03/00536

MODULARIO I.C.A. - 101

Mod. C.E. - 1-4-7

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Roma, lì 30 SET. 2003

IL DIRIGENTE
Dr. A. CAPONE

PCT

REQUEST

The undersigned requests that the present international application be processed according to the Patent Cooperation Treaty.

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PCT/IT 02 / 00651
International Application No.

01 OCT 2002 11/10/02
International Filing Date

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Name of receiving Office and "PCT International Application"

Applicant's or agent's file reference *(if desired) (12 characters maximum)* BPC412

Box No. I TITLE OF INVENTION
System and process for measuring, compensating and testing numerically controlled machine tool heads and/or tables

Box No. II APPLICANT ☐ This person is also inventor

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

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Box No. III FURTHER APPLICANT(S) AND/OR (FURTHER) INVENTOR(S)

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country. The country of the address indicated in this Box is the applicant's State (that is, country) of residence if no State of residence is indicated below.)*

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This person is:
☐ applicant only
☒ applicant and inventor
☐ inventor only *(If this check-box is marked, do not fill in below.)*

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State *(that is, country)* of residence: IT

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☐ Further applicants and/or (further) inventors are indicated on a continuation sheet.

Box No. IV AGENT OR COMMON REPRESENTATIVE; OR ADDRESS FOR CORRESPONDENCE

The person identified below is hereby/has been appointed to act on behalf of the applicant(s) before the competent International Authorities as: ☒ agent ☐ common representative

Name and address: *(Family name followed by given name; for a legal entity, full official designation. The address must include postal code and name of country.)*

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☐ **Address for correspondence:** Mark this check-box where no agent or common representative is/has been appointed and the space above is used instead to indicate a special address to which correspondence should be sent.

Box No. V DESIGNATION OF STATES *Mark the applicable check-boxes below; at least one must be marked.*

The following designations are hereby made under Rule 4.9(a):

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Precautionary Designation Statement: In addition to the designations made above, the applicant also makes under Rule 4.9(b) all other designations which would be permitted under the PCT except any designation(s) indicated in the Supplemental Box as being excluded from the scope of this statement. The applicant declares that those additional designations are subject to confirmation and that any designation which is not confirmed before the expiration of 15 months from the priority date is to be regarded as withdrawn by the applicant at the expiration of that time limit. *(Confirmation (including fees) must reach the receiving Office within the 15-month time limit.)*

Box No. VI PRIORITY CLAIM

The priority of the following earlier application(s) is hereby claimed:

Filing date of earlier application *(day/month/year)*	Number of earlier application	Where earlier application is: national application: country or Member of WTO	regional application:* regional Office	international application: receiving Office
item (1)				
item (2)				
item (3)				
item (4)				
item (5)				

☐ Further priority claims are indicated in the Supplemental Box.

The receiving Office is requested to prepare and transmit to the International Bureau a certified copy of the earlier application(s) *(only if the earlier application was filed with the Office which for the purposes of this international application is the receiving Office)* identified above as:

☐ all items ☐ item (1) ☐ item (2) ☐ item (3) ☐ item (4) ☐ item (5) ☐ other, see Supplemental Box

* *Where the earlier application is an ARIPO application, indicate at least one country party to the Paris Convention for the Protection of Industrial Property or one Member of the World Trade Organization for which that earlier application was filed (Rule 4.10(b)(ii)):* ....

Box No. VII INTERNATIONAL SEARCHING AUTHORITY

Choice of International Searching Authority (ISA) *(if two or more International Searching Authorities are competent to carry out the international search, indicate the Authority chosen; the two-letter code may be used)*:

ISA / ....

Request to use results of earlier search; reference to that search *(if an earlier search has been carried out by or requested from the International Searching Authority)*:

Date *(day/month/year)* Number Country *(or regional Office)*

Box No. VIII DECLARATIONS

The following **declarations** are contained in Boxes Nos. VIII (i) to (v) *(mark the applicable check-boxes below and indicate in the right column the number of each type of declaration)*:

			Number of declarations
☐	Box No. VIII (i)	Declaration as to the identity of the inventor :	
☐	Box No. VIII (ii)	Declaration as to the applicant's entitlement, as at the international filing date, to apply for and be granted a patent :	
☐	Box No. VIII (iii)	Declaration as to the applicant's entitlement, as at the international filing date, to claim the priority of the earlier application :	
☒	Box No. VIII (iv)	Declaration of inventorship (only for the purposes of the designation of the United States of America) :	1
☐	Box No. VIII (v)	Declaration as to non-prejudicial disclosures or exceptions to lack of novelty :	

Box No. VIII (iv) DECLARATION: INVENTORSHIP (only for the purposes of the designation of the United States of America)
The declaration must conform to the following standardized wording provided for in Section 214; see Notes to Boxes Nos. VIII, VIII (i) to (v) (in general) and the specific Notes to Box No. VIII (iv). If this Box is not used, this sheet should not be included in the request.

Declaration of inventorship (Rules 4.17(iv) and 51*bis*.1(a)(iv)) for the purposes of the designation of the United States of America:

I hereby declare that I believe I am the original, first and sole (if only one inventor is listed below) or joint (if more than one inventor is listed below) inventor of the subject matter which is claimed and for which a patent is sought.

This declaration is directed to the international application of which it forms a part (if filing declaration with application).

This declaration is directed to international application No. PCT/............................ (if furnishing declaration pursuant to Rule 26*ter*).

I hereby declare that my residence, mailing address, and citizenship are as stated next to my name.

I hereby state that I have reviewed and understand the contents of the above-identified international application, including the claims of said application. I have identified in the request of said application, in compliance with PCT Rule 4.10, any claim to foreign priority, and I have identified below, under the heading "Prior Applications," by application number, country or Member of the World Trade Organization, day, month and year of filing, any application for a patent or inventor's certificate filed in a country other than the United States of America, including any PCT international application designating at least one country other than the United States of America, having a filing date before that of the application on which foreign priority is claimed.

Prior Applications: ....

I hereby acknowledge the duty to disclose information that is known by me to be material to patentability as defined by 37 C.F.R. § 1.56, including for continuation-in-part applications, material information which became available between the filing date of the prior application and the PCT international filing date of the continuation-in-part application.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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Mailing Address: Via San Felice 98 - I-10025 PINO TORINESE - ITALY

Citizenship: Italian

Inventor's Signature: ....
(if not contained in the request, or if declaration is corrected or added under Rule 26*ter* after the filing of the international application. The signature must be that of the inventor, not that of the agent)

Date: 07.10.2002
(of signature which is not contained in the request, or of the declaration that is corrected or added under Rule 26*ter* after the filing of the international application)

Name: ....

Residence: ....
(city and either US state, if applicable, or country)

Mailing Address: ....

Citizenship: ....

Inventor's Signature: ....
(if not contained in the request, or if declaration is corrected or added under Rule 26*ter* after the filing of the international application. The signature must be that of the inventor, not that of the agent)

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☐ This declaration is continued on the following sheet, "Continuation of Box No. VIII (iv)".

Box No. IX CHECK LIST; LANGUAGE OF FILING

This international application contains:

(a) the following number of sheets in paper form:

request (including declaration sheets) :	5
description (excluding sequence listing part) :	25
claims :	7
abstract :	1
drawings :	14
Sub-total number of sheets :	52
sequence listing part of description *(actual number of sheets if filed in paper form, whether or not also filed in computer readable form; see (b) below)* :	-
Total number of sheets :	52

(b) sequence listing part of description filed in computer readable form

(i) ☐ only (under Section 801(a)(i))

(ii) ☐ in addition to being filed in paper form (under Section 801(a)(ii))

Type and number of carriers (diskette, CD-ROM, CD-R or other) on which the sequence listing part is contained *(additional copies to be indicated under item 9(ii), in right column)*: ....

This international application is accompanied by the following item(s) *(mark the applicable check-boxes below and indicate in right column the number of each item)*: — **Number of items**

1. ☒ fee calculation sheet :
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4. ☐ copy of general power of attorney; reference number, if any: .... :
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6. ☐ priority document(s) identified in Box No. VI as item(s): .... :
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10. ☐ other *(specify)*: .... :

Figure of the drawings which should accompany the abstract: Fig. 6

Language of filing of the international application: ENGLISH

Box No. X SIGNATURE OF APPLICANT, AGENT OR COMMON REPRESENTATIVE

Next to each signature, indicate the name of the person signing and the capacity in which the person signs (if such capacity is not obvious from reading the request).

Paolo Garavelli

Paolo Garavelli
Applicants' Agent

ATTIVITA' PRODUTTIVE

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1. Date of actual receipt of the purported international application:	11 OCT 2002 11/10/02
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4. Date of timely receipt of the required corrections under PCT Article 11(2):	
5. International Searching Authority (if two or more are competent): ISA /	6. ☐ Transmittal of search copy delayed until search fee is paid

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SYSTEM AND PROCESS FOR MEASURING, COMPENSATING AND TESTING NUMERICALLY CONTROLLED MACHINE TOOL HEADS AND/OR TABLES

The present invention relates to processes for measuring, compensating and testing rotary heads and/or tables for numerically controlled machine tools and to an hardware and software system that performs such processes.

The invention will be described and shown hereinbelow as applied to machine heads, but obviously everything that is described can be similarly applied to systems with head + table or only machine tool tables obtaining the same inventive effects and advantages, since simple cartesian reference systems conversions are hereby involved.

The rotary heads (hereinbelow called "heads") of numerically controlled machine tools are machine tools axes controlled through a numeric control (CNC). These heads are commonly equipped with one or two rotation degrees of freedom. Possible variations to such configuration, that has to be deemed included within the scope of the present invention, are rotary heads in which the rotation movements are partially or wholly decomposed on rotating tables.

The hardware system, that will be described hereinbelow, allows measuring with automatic processes enough values so that measuring processes and softwares can process compensations and tests of this part of the machine.

The term "geometric measure" of the heads means the measure of geometric head errors. These errors are generated by an incorrect component assembling, by an incorrect realisation of the components or by the component weights. Hereinbelow a more detailed classification of these error types will also be explained.

The term "compensation" of the heads means the software correction of the measured errors within the numeric control. As previously mentioned, an error classification will be given below and therefrom the related software compensation algorithms will follow. The compensation further includes both a measuring software and a compensation software. The measuring software allows performing and processing the measuring data while the compensation software performs corrections of measured and processed errors.

The term "automatic processes" of the heads means a series of automatic machine movements that, through the hardware system, collect measures that the measuring software processes to create compensation software input data.

The term "dynamic test" of the heads means the measure of dynamic responses of machine movements that involve rotation head axes. Typically, these tests point out "twitching" and "ripple" problems for these axes.

Currently, there are no dynamic test systems for the heads, while there are manual or semi-automatic geometric measuring processes: these latter ones, above all for the purposes of the present invention, are not systems that are integrated in the numeric control and they do not allow the freedom to suit at will the complexity of the

error model that has to be described by performing the measures.

The current geometric measures provide for the use of measuring systems, such as decimal or millesimal comparators, and artifacts, such as certified squares, control cylinders (commonly called "gage tools"), etc. The measure operator, with a series of known manual operations, after having assembled and repeatedly positioned the above mentioned artifacts, takes note of the measure values. The semi-automatic processes mainly use digital feeler devices (see for example the Renishaw system MP10) and a reference artifact (mainly a ball). With measuring processes it is thereby possible to obtain part of the values that can be measured with the manual system. The major problem with these known techniques is that they make the integration with the numeric control difficult and make the use of complex compensation models unfeasibile, since the number of measures to be performed and the timing generated by such technique would be excessively long and cumbersome.

One of the limits of such applications is that not all the necessary measures and/or variables for the geometric head measure can be automatically measured, as can be well seen from the schematic drawings in Fig. 1. In such Figure, it can be seen that the parallelism check between the axis of head 1 equipped with two parts 3 and 5 and a stem 7 in a mutual rotation movement, and the reference cartesian axes is carried out through a measuring instrument (commonly called " gage tool") 9 placed next to the stem 7. The limits of such type of operation essentially are the adopted measuring systems and the following limited measuring processes.

Object of the present invention is solving the prior art deficiencies, by providing a system and a process for measuring, compensating and testing numerically controlled machine tool heads that allow obtaining the following innovations:

a) an instrument, and therefore processes, for automatically performing the geometric measures integrating such system into the numeric control;
b) the chance of increasing the complexity of such measures in order to describe more complex head errors, always having however measure execution times that are extremely reduced with respect to the prior art;
c) the use of such instrument for dynamic tests;
d) the use of known correction systems to perform the compensation of measured errors.

The above and other objects and advantages of the invention, as will appear from the following description, are reached by a system and processes as disclosed in Claims 1, and 8, 20 and 21. Preferred embodiments and non-trivial variations of the present invention are disclosed in the dependent Claims.

The present invention will be better described by some preferred embodiments, provided as a non-limiting example, with reference to the enclosed drawings, in which:

- Figure 1 is a schematic view that shows the measuring steps of axis quadrature in the prior art;
- Figures 2A to 2D are views of the support base 11 part of an embodiment of the system of the present invention;
- Figure 3 is a side view of the gage tool part of an embodiment of the system of the present invention;

- Figures 4A to 4C are schematic views of an embodiment of the head of the system of the invention with related geometric models;
- Figures 5A to 5C are schematic views of another embodiment of the head of the system of the invention with related geometric models;
- Figure 6 is a schematic view of an embodiment of the system of the invention;
- Figures 7A to 7C are schematic views that exemplify the way in which the measured amounts are shown;
- Figures 8A to 8C are schematic views that show the movements of the support base 11 of Fig. 2A to 2D;
- Figure 9 is a schematic view that shows an application example of the system of the invention;
- Figures 10 to 13 are schematic views of further steps in the example in Fig. 9;
- Figures 14A and 14B are schematic views that show a further application example of the system of the invention;
- Figure 15 is a perspective view that shows some operating positions of the system of the invention;
- Figure 16 is a schematic view that shows the nutator head;
- Figures 17 to 21 are schematic views of the movements of the system of the present invention; and
- Figures 22 to 24 are vector graphs that show the actions of the head model of the present invention.

With reference to the Figures, a preferred, but non-limiting embodiment of the system of the present invention is shown. The system will be described hereinbelow as applied to the field of measuring, compensating and testing numerically controlled machine tool heads 1, but it is obvious that it can find a valid and efficient

application to any field in which a completely automated, accurate and reliable measure of object positions in reference systems is necessary.

With reference to the Figures, and in particular to Fig. 2 to 5, the system for measuring, compensating and testing numerically controlled machine tool heads (1) and/or tables substantially comprises:

- at least one support base 11 equipped with a plurality of distance sensors 14;
- at least one device 16 of the gage tool type composed of an elongated cylinder 17; the cylinder 17 is equipped at one of its ends with connection means 18 for the heads 1 and is equipped at another opposite end with a ball 20, that is placed next to the sensors 14 so that they are able, always and in any position, to measure the distance that separates them from the ball 20.

In particular, the support base 11 can be of a circular shape and is preferably equipped with three distance sensors 14 placed on the base in positions that are mutually offset by 120°. Instead, the connection means 18 are of the tapered type and the heads 1 are adapted to receive, in one of their moving parts 3, 5, the connection means 18 for the unmovable connection thereto during the measures.

According to what is shown in Fig. 6, the system of the invention is operatively coupled to processing means 30 comprising means 31 for performing processes for measuring errors that can be modelled, means 32 for performing processes for measuring errors that cannot be modelled and means 33 for performing dynamic checks. Moreover, the heads 1 are operatively coupled with test and control means 34 also comprising means 35 for performing

compensation processes of errors that can be modelled and means 36 for performing compensation processes of errors that cannot be modelled.

According to the measure of positioning errors of the ball 20 of the gage tool 16, that ideally shows the tool tip, two possible processes can be obtained:

1) the head 1 is moved by using already active compensations (those of errors that can be modelled). Then the CNC deems to have kept the ball 20 centre unmoved (in CNC systems this type of movement is commonly called movement with enabled RTCP). The error measure can be carried out using one of the following alternatives:
   a) The values provided by the sensors 14 of the support base 11 can be transformed into real coordinates of the ball 20 of the gage tool 16. The difference between theoretical coordinates and real coordinates of the ball 20 shows the measured errors.
   b) The values provided by the sensors 14 of the support base 11 can be used to correct the position of the machine linear axis in order to take back the ball 20 to the point where the sensors 14 provide the initial values. In this way the ball 20 will not have been moved but otherwise the linear axis will have performed an additional movement with respect to the one that the CNC would have imposed to them depending on currently active compensations. Such correction are the measured errors.

2) The head is handled without using any active compensation in the CNC. Through the previously-listed process b, the linear axes position is corrected in order to take back the ball 20 to the point in which the sensors 14 provide the initial values. Such induced movements

represent the indirect error measure for computation purposes.

As regards the error detection mechanism, through a software that can be easily and readily realised that performs some transforming, the support base 11 with the sensors 14 provides the position of the ball 20 of the gage tool 16. The process to detect the position of the ball 20 is known in the art and will not be described in further detail in this context. For measuring the errors, it is necessary to perform a calibration process of the sensors 14 of the support base 11 (such process is known in the art and will not be described herein in detail).

Independently from the technique used to extract the positioning errors from the controlled movements to the machine, as shown in Fig. 7A to 7B, the measuring system is idealised assuming that the machine displacement (desired displacement + measured errors) is able to be measured. In Fig. 7A, a displacement error A of the head 1 axis is shown, depending on which, as shown in Fig. 7B, a measured error D occurs following the programmed movement of the head 1 from a position B to a position C, such movement being represented by the corresponding arrows in the Figure. The situation in Fig. 7C thereby occurs, that shows the diagram of the performed measure.

As regards the error measuring process, the advantages of the configuration of the system with sensors 14 and support base 11 as a tripod are:

1) Enough measuring accuracy in order to determine the centre of the ball 20 of the gage tool 16 and therefore the errors to be measured. The sensors 14 can be realised using different technologies and can provide or not the contact with the ball 20 of the gage tool 16. When distance sensors 14 are used instead of the

contact ones and of a capacitive type, the support base 11 can be shaped as a hollow spherical cover (not shown) whose focal point is the centre of the ball 20 of the gage tool 16. This in order to minimise capacitive measures noises. Such modification (and similar ones) must not be deemed as variations from the basic concept of the support base 11 as previously described.

2) Possibility of slanting the gage tool 16 below the horizontal line without collisions between moving bodies and measuring instrument. The wide range of positions that can be reached for the measures allows the measuring software to inspect thereby all interesting head positions.

According to what is shown in Fig. 8A to 8C, the support base 11 can be connected to bearing means 40 adapted to allow a rotation of the support base 11 itself up to 90° with respect to its own axis (F), in order to reach a plurality of operating positions between two mutually perpendicular extreme axes (F, G). The bearing means 40 are further adapted to simultaneously allow a rotation of the support base 11, once having reached the extreme axis (G) position, around the axis (F) perpendicular thereto.

As regards the geometric measure process of the head 1, as described previously, the automatic measures allowed by the measuring instrument and the measure processes, allow increasing the complexity degree of the geometric head model. In this context, the term "geometric model" of the head 1 means the mathematical model that describes the real behaviour of the head 1 with respect to the

theoretical one. The parameters of such model are those that are obtained through the measures.

Fig. 4A to 4C and 5A to 5C show some types of heads and the related simplified geometric models that are used today related to a possible more complex model that can be used with the system described here.

The parameters of these geometric models can be called errors that can be modelled meaning that a possible compensation system is able to use these parameters to compute the errors that the CNC must correct for working purposes. These latter errors are for example positioning errors of the tool end (tool tip).

When the head 1 has been compensated by using the above described system, it will have a series of errors that the used model, though more complex, does not describe. These errors, that can be called errors that cannot be modelled, result into a still incorrect tool tip positioning. The instrument described here (but also equivalent instruments such as digital feeler pins and reference balls) is also able to perform the measure of these residual errors.

It will now be demonstrated that the described system is able to provide necessary data for identifying the parameters of a geometric model of a head 1 selected as an example. The demonstration is divided into three examples that describe geometric models with increasing complexity for measuring the errors that can be modelled and a further example that describes the measure of the errors that cannot be modelled.

For better clarifying, the examples of procedures will include:

Example 1) Procedure for measuring a head with a simple geometric model

Example 2) Procedure for measuring a head with a complex geometric model

Example 3) Procedure for measuring a head using an algorithm for solving complex models

Example 4) Procedure for measuring errors that cannot be modeled

EXAMPLE 1:

Let us take into account the geometric model described in Fig. 9 where it is assumed as an example that the axes runs are A [0;360] B [-90;90] (refer to Fig. 9):

The parameters of this model are:

- Angular positioning accuracy for axes A and B.
- Direction and rotation centre of axes A and B. The exact orientation of the rotation axis must be located in order to determine the parallelism position between rotation axis and linear axis.
- Zero pre-set of axes A and B. The 0 pre-set shows the position in which an axis is programmed in position 0. For a head the 0 pre-set is the point in which the tool is aligned with axis Z.
- P (commonly called pivot), DY (distance between rotation axis for axis B and axis A), DTy (distance in plane YZ between gage tool axis and rotation axis for axis A), DTx (distance in plane XZ between gage tool axis and rotation axis for axis A)

It must be noted that the figure in plane YZ assumes that the 0 pre-set for axis A has already been located. Otherwise the distance between the rotation axis would have, in addition to a component DY, also a component DX since the rotation axis of axis B would not be

perpendicular to plane YZ. It is for such reason that before computing DY, the 0 pre-sets are computed.

For easy of exposure in the figure the rotation axes are shown parallel to the linear axis. In practice this is obtained after having measured and corrected the parallelism between rotation axes and linear axis.

The measuring procedure consists in the following steps:

Step 1:

Head positioning A=0 B=90°.

Movement of axis A from 0° to 360° and positioning errors acquisition for a defined pitch in axis A movement.

A series of points is then measured that describe a circle. The circle equation can be computed with known quadratic error minimising methods.

From the measured points (which have an univocal relationship with axis A transduced position) it is possible to determine the angular positioning accuracy for axis A.

From the circle equation it is possible to determine the rotation axis slant for axis A with respect to axis Z (parallelism between rotation axis A and linear axis Z).

From the measured points it is then possible to determine which is the axis A transducer value for which the measured points lie in plane YZ. The 0 pre-set for axis A is thereby determined.

It must be noted that the errors in axis B (0 pre-set, parallelisms and transducer linearity) have no influence whatsoever.

Step 2:

With a similar procedure to the one in step 1, the head is positioned A=0 B=90° and a movement of axis B is carried out from 90° to -90° and a positioning error

acquisition is carried out for a defined pitch in axis B movement (see Fig. 15).

A series of points is then measured that describe a semicircle. The circle equation can be computed with the known quadratic error minimising methods.

From the measured points (which have an univocal relationship with axis B transduced position) it is possible to determine the angular positioning accuracy for axis B.

From the circle equation it is possible to determine the rotation axis slant for axis B with respect to axis X (parallelism between rotation axis B and linear axis X).

From the measured points it is then possible to determine which is the axis B transducer value for which the measured points lie in plane XZ. The 0 pre-set for axis B is thereby determined.

At this time both for axis A and for axis B the following are known: angular positioning accuracy, parallelism between rotation axes and linear axis, zero pre-set. By activating such parameters in the compensation software or by taking into account their value in the measuring software, it can be assumed that their effects have been cancelled and thereby the head has been driven to the condition described in the starting figure.

Step 3:

Errors in positions A=0 B=0 and A=180 B=0 are measured (see Fig. 10).

The relationship: 2*DTx = X is obtained,

where X is the index of a value that can be measured through the gage tool (see Fig. 3) + tripod (see Fig. 2) measuring system.

Step 4:

Errors in positions A=0 B=0 and A=180 B=0 are measured (see Fig. 11).

The relationship: 2*(DY+DTy) = Y is obtained,

where Y is the index of a value that can be measured through the gage tool + tripod measuring system.

Step 5:

Errors in positions A=0 B=-90 and A=180 B=90 are measured (see Fig. 12).

The relationship: 2*DTy = Z is obtained,

where Z is the index of a value that can be measured through the gage tool + tripod measuring system.

Step 6:

Errors in positions A=0 B=-90 and A=180 B=-90 are measured (see Fig. 13).

The relationship: 2*(DY + P) = Y is obtained,

where Y is the index of a value that can be measured through the gage tool + tripod measuring system.

The equations found in steps 3 to 6 are all independent and their resolution is mathematically able to be demonstrated.

With a similar procedure a nutator head can be measured.

Fig. 16 shows a simplified geometric model of a generic head 1 (nutator head). It is assumed as an example that the axes runs are A [0;360] B [-180;180]

The parameters (or errors to be measured) in this model are:

- Angular positioning accuracy for axes A and B.
- Direction and rotation centre for axes A and B.
- Zero pre-set for axes A and B.
- DTx, DX, DTy, DY and P. The angle (α) of 45° is assumed as known. The measures to be carried out

are 5 and the support base 11 settings are always those of the basic configuration.

As in the previous case in Fig. 16 the rotation axes are shown as parallel to the theoretical configuration (axis A parallel to axis Z and axis B in plane XZ at 45° from axis X). In practice this is obtained after having measured and corrected the parallelism between rotation axes and linear axis and obtained the 0 pre-sets.

The measuring procedure consists in the following steps:

Step 1:

As in the previous case, a circle is performed for measuring axis A. B is placed at 180° (gage tool in plane XY) and the measure is performed by moving A from 0 to 360 degrees.

The operations to be performed are the same ones and it is thereby obtained: angular positioning accuracy for axis A; parallelism between rotation axis A and axis Z; 0 pre-set for axis A for which the gage tool lies in plane XZ.

Step 2:

As in the previous case, a circle is performed for measuring axis B. A is placed at 0° and the measure is performed by moving B from -180 to +180 degrees.

The series of points describe a circle that lies on a plane that ideally should intersect plane YZ in a straight line parallel to Y and plane XZ in a straight line slanted by -45° with respect to X. Deviations from such configuration will be parallelisms corrections for axis B.

As previously the corrections are detected in order to correct the angular positioning accuracy for B and the 0 pre-set for which the gage tool is vertical.

Like in the previous example, being known both for axis A and for axis B transducer linearity, parallelism between rotation axes and linear axis and zero pre-set, the head has been driven to the condition described in Fig. 16.

Step 3:

In Fig. 17, the following is applied:

Movement:

A0 => 180

B0

Relationship:

DTx + DX = X

Step 4:

In Fig. 18, instead, the following is applied:

Movement:

A0

B0 => 180

Relationship:

P - DTx = X

Step 5:

In Fig. 19, the following is applied:

Movement:

A0 => 180

B180

Relationship:

2P + 2DX = X

Step 6:

In Fig. 20, the following is applied:

Movement:

A0 => 180

B0

Relationship:

2DY + 2DTy = X

Step 7:

In Fig. 21, the following is applied:

Movement:

A0

B0 => 180

Relationship:

2DTy = Y

P = Z

The equations found in steps 3 to 7 are all independent and their resolution is mathematically able to be demonstrated.

If angle α shown in the Figures is not 45° and is not known with accuracy, by using the analytical method described below, such angle would be measurable.

EXAMPLE 2:

Figures 22 to 24 show an advanced geometrical model of a generic head 1. The parameters (or errors to be measured) of this model are: αx, βx, DBx, DTx, P, αt, αy, βy, DBy, DTy, βt.

In these models the non-parallelisms are pointed out for the rotation axes with respect to linear axis (αx, βx, αy, βy). Such parameters are measured with the same procedures mentioned in steps 1 and 2 which further allow obtaining the transducer linearity and the 0 pre-set value.

Having measured such parameters and by activating the compensation software or taking into account such values within the measuring software, it can be ideally assumed to have corrected such errors and have transformed the affected head into a simpler model (see Fig. 14A).

Or, according to which is the reference model, see the example in Fig. 14B.

As an example refer to the case in the second figure.

With respect to the model in example 1, we have parameters αt and βt more and thereby performing steps 3 to 6 plus other two steps that describe independent positions and equations, again a series of equations is found that are arithmetically able to be solved. It must be noted that for this model DTx+DX is a single variable (from now on DX).

The steps therefore are:

Step 3: positions A=0 B=0 and A=180 B=0

Relationship: $2*(DX + P*\sin(\alpha t)) = X$

Step 4: positions A=0 B=0 and A=180 B=0

Relationship: $2*(DY + DTy + P*\sin(\beta t)) = Y$

Step 5: positions A=0 B=-90 and A=180 B=90

Relationship: $2*(DTy + P*\sin(\beta t)) = Z$

Step 6: positions A=0 B=-90 and A=180 B=-90

Relationship: $2*(DY + P*\cos(\beta t)) = Y$

Step 7: positions A=0 B=-90 and A=0 B=90

Relationship: $2*(P*\sin(\beta t)) = Y$

Step 8: positions A=0 B=0 and A=0 B=-90

Relationship: $P*\sin(\beta t) - DTy - P*\cos(\beta t) = Y$

$$P*\sin(\beta t) + DTy + P*\cos(\beta t) = Z$$

Summarising the processes disclosed in Examples 1 and 2, it is still possible to locate the following macro-steps for a generic head 1:

1. for a head (20), there are planes in which the circumference described by the tool tip lies when the following movements are realised:

- axis B at 90°; axis A that performes one revolution (circle 1)
- axis A at 0°; axis B that performs one revolution (circle 2),

these planes are perpendicular and parallel to machine tool cartesian axes; such process comprises the steps of:

- executing the circle 1;
- rebuilding with mean square methods or the like the circle 1 through a series of points describing it;
- locating the non-parallelism of the plane passing through the circle 1 with respect to the plane that is orthogonal to the ideal rotation axis of axis A;
- locating the relationship between position transduced by axis A measuring systems and related tool tip location point and then computing the angular positioning accuracy of axis A;
- executing the circle 2;
- rebuilding with means square methods or the like the circle 2 through a series of points describing it;
- locating the non-parallelism of the plane passing through the circle 2 with respect to the plane that is orthogonal to the ideal rotation axis for axie B;
- locating the axis A position 0 through the component of the previously desceibed angles that lies in the plane perpendicular to the ideal rotation axis of axis A;
- locating the axis B position 0 through the measured point on circle 2 that allows having the tool as vertical; and
- locating the relationship between position transduced by axis B measuring systems and related tool tip positioning point and then computing the angular positioning accuracy of axis B

2. according to the geometric model of the head 1 that has to be described, and therefore to the number of parameters that are still not known, a sequence of positionings of the head 1 is performed, adapted to obtain

algebraic equations that link the above parameters to the measured errors; such equations must be linearly independent and must be equal to the number of parameters to be determined.

EXAMPLE 3

The geometric model complexity could further increase (therefore increase the number of model parameters) till the search of solutions through algebraic equations that describe independent positions is made difficult. In this case more complex mathematics and more sophisticated solution algorithms could simply be adopted.

More complex models are for example the Rodriguez-Hamilton models that describe the 6 degrees of freedom for coupling two bodies. In this case our error model would have 6 degrees of errors for axis A movement, 6 for B axis movement and 6 for gage tool rotation in the spindle.

In order to solve such type of problem, known techniques can be adopted that solve mathematical problems or models depending on a series of experimental measures (our error measures in the different head positions). These techniques are based on minimising mean square errors or on using neural algorithms (as known in the art, for example, from: Kim K., Kim M.K. "Volumetric Accuracy based on Generalised Geometric Error Model in Multi-Axis Machine Tool", Mec. Mach. Theory, Vol. 26 (1991) No. 2, pages 207-219; Duffie N.A., Yang S.M., "Generation of Parametric Kinematic Error-Compensation Functions for Volumetric Error Measurements", Annals of the CIRP, Vol. 34/1/1985, pages 435-438; D.R. Hush et al., "An Overview of Neural Networks", Informàtica y Automàtica, vol 25, 1992; T. Moriwaki, C. Zhao, "NN Approach to Identify Thermal Deformation of Machining Center", Human Aspects in

Computed Integration; and J.C. O'Brien; J.R. Leech, "Can Neural Nets Work in Condition Monitoring", Comadem 92 , 1992, pages 88-93).

The result provided by such techniques is a computation engine that, given the desired model, acquires measures till the model is solved by discarding redundant measures or measures that create bad problem conditionings and solution instability.

This process allows extending the patent applicability to every kind of configuration of head 1 and/or head with table. The model can thereby arrive to such complexities as to also take into account possible positioning errors of the ball 20 of the gage tool 16 deriving from movement errors of the linear axis (those that move the head 1).

If the error compensation software that resides in the CNC has not the same degree of complexity of the measuring software, the same measuring software would perform the translation of parameters in its model into the parameters of the compensation software module. The requirement of such translation is always obtaining the least degree of residual errors in the head 1.

EXAMPLE 4:

As regards the measuring process for the errors that cannot be modelled, all errors not included in the geometric model being used are still a reason for positioning errors as regards programmed movements of the head 1 axis.

For such errors it is thereby possible to establish only an empirical link with the position of the head 1 axis. The relationship will thereby be univocal. Given a position of the two half-bodies A and B, there are three error values DX, DY and DZ in positioning the tool tip.

The only algebraic relationship is linked to the tool length, such relationship being able to be established only by identifying the three values DX, DY and DZ, for a given A and B, with two tool length values (therefore the measures for every head 1 position are two, with two gage tools 16 with a known and distinct length). For a generic tool length, the error is a linear interpolation of the pair of three measured values DX, DY and DZ.

The measuring process is therefore measuring errors DX, DY and DZ of the ball 20 of the gage tool 16 for all affected positions A and B. The measures are carried out first with a gage tool 16 and then with the following gage tool 16. The affected positions could be all combinations of positions of the two axes from their negative end to their positive end, discretising with a step to be empirically found or with analysis algorithms for error frequencies.

The measure of errors that cannot be modelled is described and solved more widely in document WO-A-00/003312 of the same Applicant of the present invention. In fact, the measure of errors that cannot be modelled is not per se an innovation of the compensation method (already described in the above document), but instead in this case the application of sensors 14 and support base 11 is relevant in order to automatically perform also this type of measures.

It is necessary to underline that a similar measuring process can be performed by using a digital feeler pin (assembled on a spindle nose) and a reference ball (placed in the machine working area).

The parameter input table for such static error compensation software will be composed as follows:

Position A	Position B	Gage tool length	DX	DY	DZ
[negative end-of-stroke]	[negative end-of-stroke]	Length 1	#	#	#
[illegible]	[negative end-of-stroke]	Length 1	#	#	#
[positive end-of-stroke]	[negative end-of-stroke]	Length 1	#	#	#
[negative end-of-stroke]	......	Length 1	#	#	#
......	......	Length 1	#	#	#
[positive end-of-stroke]	......	Length 1	#	#	#
[negative end-of-stroke]	[positive end-of-stroke]	Length 1	#	#	#
......	[positive end-of-stroke]	Length 1	#	#	#
[positive end-of-stroke]	[positive end-of-stroke]	Length 1	#	#	#
[negative end-of-stroke]	[negative end-of-stroke]	Length 2	#	#	#
......	[negative end-of-	Length 2	#	#	#

	stroke]				
[positive end-of-stroke]	[negative end-of-stroke]	Length 2	#	#	#
[negative end-of-stroke]	......	Length 2	#	#	#
......	......	Length 2	#	#	#
[positive end-of-stroke]	......	Length 2	#	#	#
[negative end-of-stroke]	[positive end-of-stroke]	Length 2	#	#	#
......	[positive end-of-stroke]	Length 2	#	#	#
[positive end-of-stroke]	[positive end-of-stroke]	Length 2	#	#	#

The error compensation software of the head 1 resides in the CNC. It is also divided into a part that performs the head movements compensation using a geometric model and a part that is the software that performs the compensation of static, that is "non geometric" (not able to be modelled) errors.

The compensation algorithms are not characterised by any degree of innovation since they are already known and they will not be further described.

As regards the dynamic head test, the above-described system of the invention can be used for checking the

dynamic behaviour of the controlled axes of the heads 1 and/or the movements of these axes combined with those of the linear axis.

By controlling through the control system 34 the movements to single machine axes, the real response on the tool tip can be observed similarly with other control means (for example the KGM system manufactured by Heidenhain).

Moreover, by controlling the combined movements between linear and rotating axes, adapted to obtain that the tool tip (now the ball 20) keeps its position in the space even during acceleration transients, the real response curve on the tool tip can be recorded.

The response curve analysis of the axes compared with the programmed one would allow analysing typical problems like "twitching" and "ripple".

The only requirement in order to be able to perform this type of test is a pass-band that is enough for the signal sampled by the system of the invention. The related pass-band can be evaluated in about 1 kHz.

It has thereby been disclosed that the system of the invention is able, through a single measure obtained by the sensors 14 and related to the distance that separates the sensors 14 themselves from the ball 20, to detect the XYZ coordinates of the center of a tool in a position of interest, instead of having, like in the prior art, to perform unaccurate measures, or measures that are not located in the XYZ space, or also measures that do not reconstruct the tool position in the real position of interest.

CLAIMS

1. System for measuring, compensating and testing numerically controlled machine tool heads (1) and/or tables, characterised in that it comprises:
- at least one support base (11) equipped with a plurality of distance sensors (14);
- at least one device (16) of the gage tool type composed of an elongated cylinder (17), said cylinder (17) being equipped at one of its ends with connection means (18) for said heads (1) and being equipped at another opposite end with a ball (20), said ball (20) being placed next to said sensors (14) so that they are able, always and in any position, to measure a distance that separates them from said ball (20).

2. System according to Claim 1, characterised in that said support base (11) is of a circular shape and is equipped with three distance sensors (14) placed on the base in positions that are mutually offset by 120°.
3. System according to Claim 1, characterised in that said connection means (18) are of a tapered shape and said heads (1) are adapted to receive, in one of their moving parts (3, 5), said connection means (18) for the unmovable connection thereto during the measures.
4. System according to Claim 1, characterised in that it is operatively coupled with processing means (30), said processing means (30) being adapted, through a single measure obtained by said sensors (14) about a distance that separates said sensors (14) from said ball (20), to detect the XYZ coordinates of a center of a tool in a position of interest.
5. System according to Claim 4, characterised in that said

processing means (30) comprise means (31) for performing measure processes for errors that can be modelled, means (32) for performing measure processes for errors that cannot be modelled and means (33) for performing dynamic checks.

6. System according to Claim 1, characterised in that said heads (1) are operatively coupled and integrated with CNC test and control means (34) also comprising means (35) for performing compensation processes for errors that can be modelled and means (36) for performing compensation processes for errors that cannot be modelled.

7. System according to Claim 1, characterised in that said support base (11) is connected to bearing means (40) adapted to allow a rotation of said support base (11) up to 90° with respect to its own axis (F), in order to reach a plurality of operating positions between two mutually perpendicular extreme axes (F, G), said bearing means (40) being further adapted to simultaneously allow a rotation of said support base (11), once having reached the extreme axis (G) position, around the axis (F) perpendicular thereto.

8. Process for measuring numerically controlled machine tool heads (1) and/or tables using a system according to Claim 1, said process comprising the steps of:

- performing a plurality of automatic measures adapted to determine the parameters of a geometric model of the head (1), said geometric model being the mathematical model that describes the real head (1) behaviour with respect to the theoretical behaviour, the parameters of said model being obtained through the measures and being called errors that can be modelled, said geometric model being of a complexity that can be freely defined by a user due to

an integration of said system with numeric control means (CNC), to a measuring accuracy provided by the system according to Claim 1, to an absence of collisions among moving parts and the system according to Claim 1 and to a quick acquisition of error measures;
- computing the detected errors that can be modelled; and
- compensating the computed errors that can be modelled through said numeric control (CNC) means for working purposes through an integrated system;
- detecting and measuring errors not described by the model being used, said errors being called errors not able to be modelled and generating a still incorrect positioning of the head (1).

9. Process according to Claim 8, characterised in that the error detecting steps are realised through said support base (11) with the sensors (14) that provides the position of the ball (20) of the gage tool (16).
10. Process according to Claim 9, characterised in that the measure of the positioning errors of the ball (20) of the gage tool (16) is carried out through the head (1) movement using compensations related to errors that can be modelled, the numeric control (CNC) means deeming to have kept the centre of the ball (20) unmoved, the difference between theoretical coordinates and real coordinates of the ball (20) being the measured errors.
11. Process according to Claim 9, characterised in that the measure of the positioning errors of the ball (20) of the gage tool (16) is carried out by using the values provided by the sensors (14) of the support base (11) that are transformed into the real coordinates of the ball (20) of the gage tool (16), the difference between theoretical coordinates and

real coordinates of the ball (20) being the measured errors.

12. Process according to Claim 9, characterised in that the measure of the positioning errors of the ball (20) of the gage tool (16) is carried out by using, as an alternative, the values provided by the sensors (14) of the support base (11) that are used to correct the machine linear axis position in order to take back the ball (20) to the point where the sensors (14) provide the initial values, the ball (20) being not moving and the linear axis performing an additional movement with respect to the one that the numeric control (CNC) means would have imposed thereto depending on currently active compensations, said correction being the measured errors.
13. Process according to Claim 11 o 12, characterised in that it further comprises a calibrating step of the sensors (14) of the support base (11).
14. Process according to Claim 8, characterised in that it is also adapted to perform an automatic measure of the angular positioning accuracy of the rotation axes and the parallelism of the rotation axes with linear axis through computing techniques used in the field of measuring and inspecting the geometric models, said techniques referring to the reconstruction of curves and/or surfaces through a series of points.
15. Process according to Claim 14, wherein, for a head (20), there are planes in which the circumference described by the tool tip lies when the following movements are realised:

- axis B at 90°; axis A that performes one revolution (circle 1)

- axis A at 0°; axis B that performs one revolution (circle 2),

said planes being perpendicular and parallel to machine tool cartesian axes; characterised in that such process comprises the steps of:

- executing the circle 1;
- rebuilding with mean square methods or the like said circle 1 through a series of points describing it;
- locating the non-parallelism of the plane passing through said circle 1 with respect to the plane that is orthogonal to the ideal rotation axis of axis A;
- locating the relationship between position transduced by axis A measuring systems and related tool tip location point and then computing the angular positioning accuracy of axis A;
- executing the circle 2;
- rebuilding with means square methods or the like said circle 2 through a series of points describing it;
- locating the non-parallelism of the plane passing through said circle 2 with respect to the plane that is orthogonal to the ideal rotation axis for axie B;
- locating the axis A position 0 through the component of the previously desceibed angles that lies in the plane perpendicular to the ideal rotation axis of axis A;
- locating the axis B position 0 through the measured point on circle 2 that allows having the tool as vertical; and
- locating the relationship between position transduced by axis B measuring systems and related tool tip positioning point and then computing the angular positioning accuracy of axis B.

16. Process according to Claim 8, characterised in that it automatically performs the head (20) positioning error measures in order to obtain a number of independent algebraic equations that allow solving the parameters of the geometric model of the head (20).

17. Process according to Claim 8, characterised in that the measures are performed by selecting a number of measures independent from the search of the model parameter resolution, extending the applicability of the process to every kind of configuration of head (1) and/or head with table, the model arriving to such complexities as to also take into account possible positioning errors of the ball (20) of the gage tool (16) deriving from movement errors of linear axis, namely the axis moving the head (1).

18. Process according to Claim 8, characterised in that, if the error compensation performed by the numeric control means (CNC) has not the same degree of complexity of the measures, the system performs the translation of the parameters of its own model into the parameters of the compensation model.

19. Process according to Claim 8, characterised in that the step of measuring the errors that cannot be modelled comprises the sub-steps of:

- establishing only an empirical link with the position of the axis of the head (1), for which the relationship will be univocal;
- performing two measures for every head (1) position through two gage tools (16) with a known and different length;
- being, for a generic length of a head (1) tool, the error a linear interpolation of the pair of three measured values DX, DY and DZ, measuring the errors DX,

DY and DZ of the ball (20) of the gage tool (16) for all affected positions, said measures being performed first with a gage tool (16) and then with a following gage tool (16);

- discretising the position combinations of the two axes from their negative end to their positive end in order to obtain the affected positions, said discretising being performed with an empirically established step or with error frequency analysis algorithms.

20. Process for testing numerically controlled machine tool heads (1) and/or tables using a system according to Claim 1, said process performing the check of the dynamic behaviour of the axes controlled by the heads (1) and/or the movements of these axes combined with the movements of the linear axis, the analysis of the response curve of the axes compared with the programmed one allowing to analyse problems like twitching and ripple, said process operating at the presence of a pass-band of at least 1 kHz of the signal sampled by the system according to Claim 1.

21. Process for compensating numerically controlled machine tool heads (1) and/or tables using a system according to Claim 1, said process being divided into a part that performs the compensation of head (1) movements using a geometric model and a part that performs the compensation of non-geometric errors or errors that cannot be modelled.

SYSTEM AND PROCESS FOR MEASURING, COMPENSATING AND TESTING NUMERICALLY CONTROLLED MACHINE TOOL HEADS AND/OR TABLES

ABSTRACT

A system and a process are disclosed, that are automated and integrated with numerically controlled systems, for measuring, compensating and testing numerically controlled machine tool heads (1) and/or tables. The system comprises: at least one support base (11) equipped with a plurality of distance sensors (14); at least one device (16) of the gage tool type composed of an elongated cylinder (17) that is equipped at one of its ends with connection means (18) for the heads (1) and is equipped at another opposite end with a ball (20), wherein the ball (20) is placed next to the sensors (14) so that they are able, always and in any position, to measure the distance that separates them from the ball (20) and determine thereby the position in the Cartesian space.

(Fig. 6.)

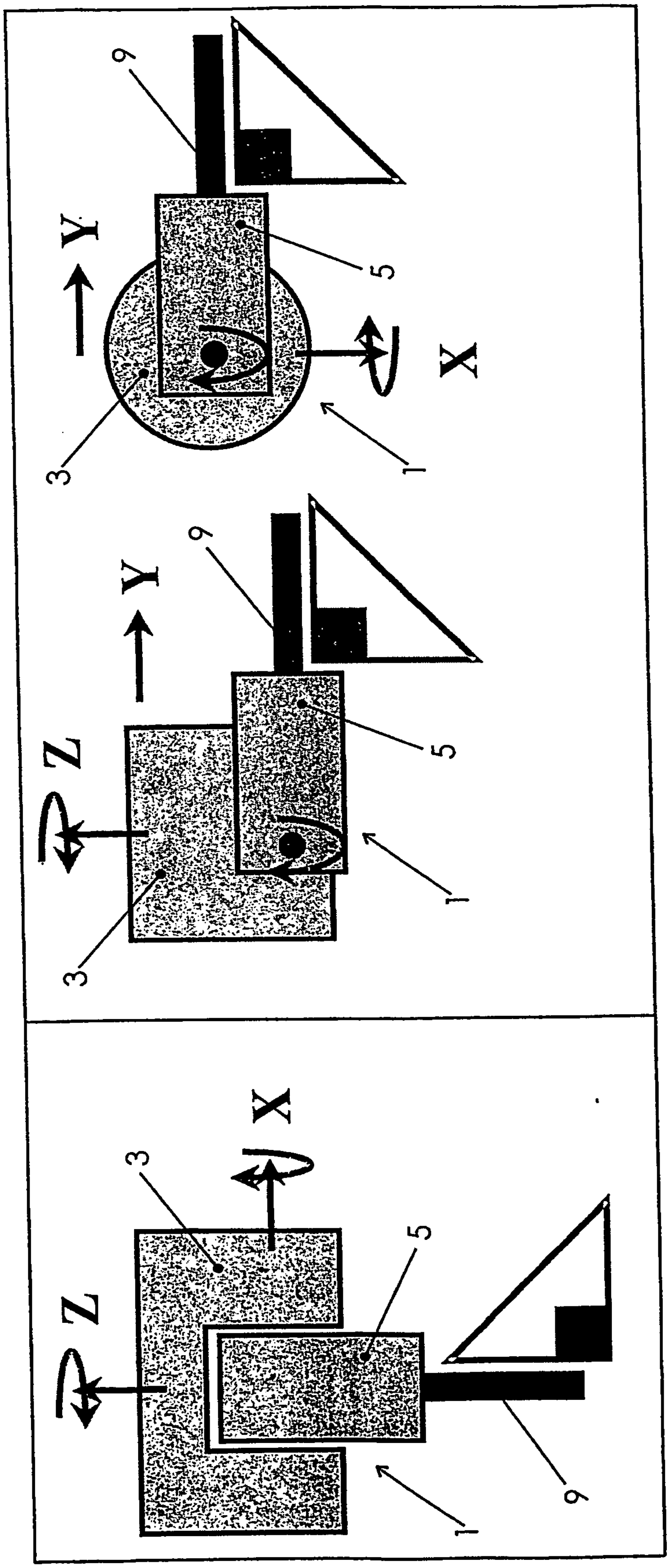

Fig. 1

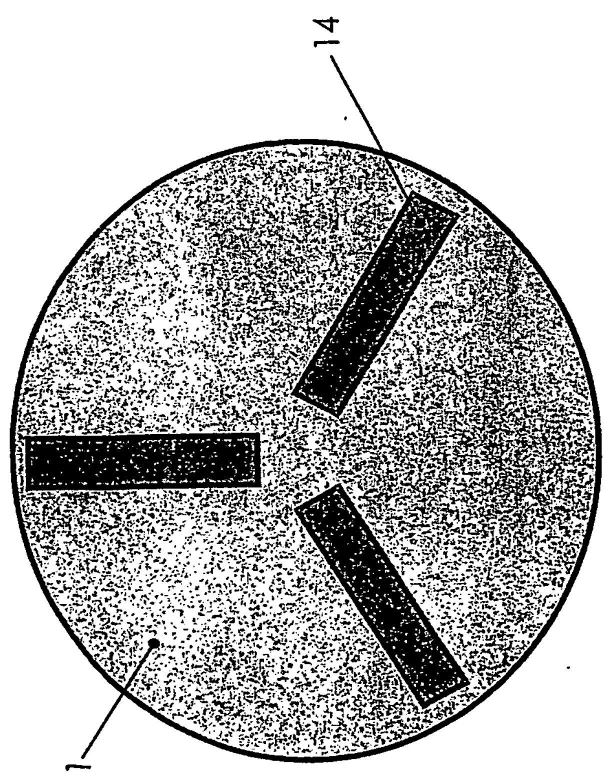

Fig. 2a

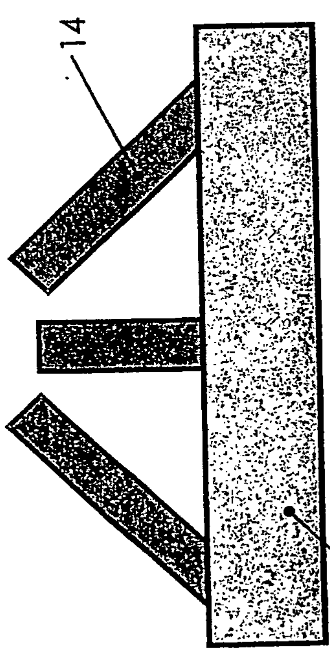

Fig. 2b

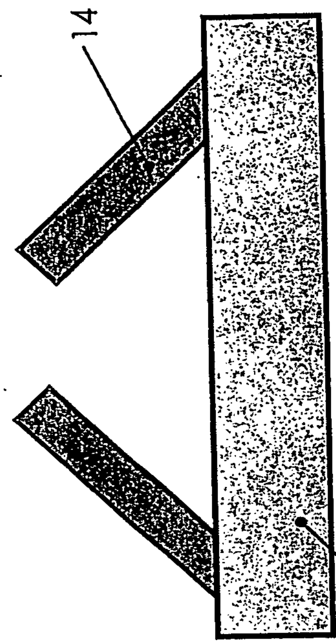

Fig. 2c

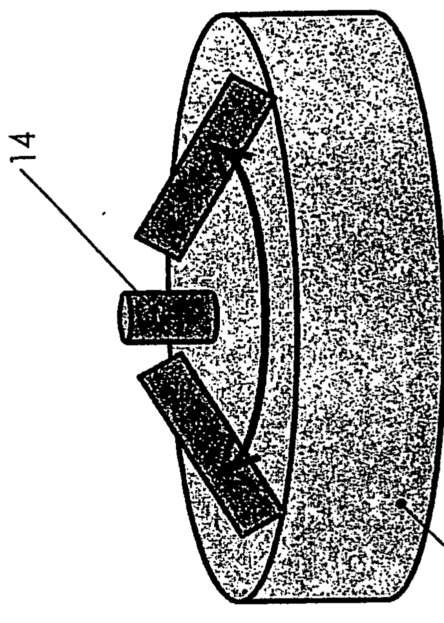

Fig. 2d

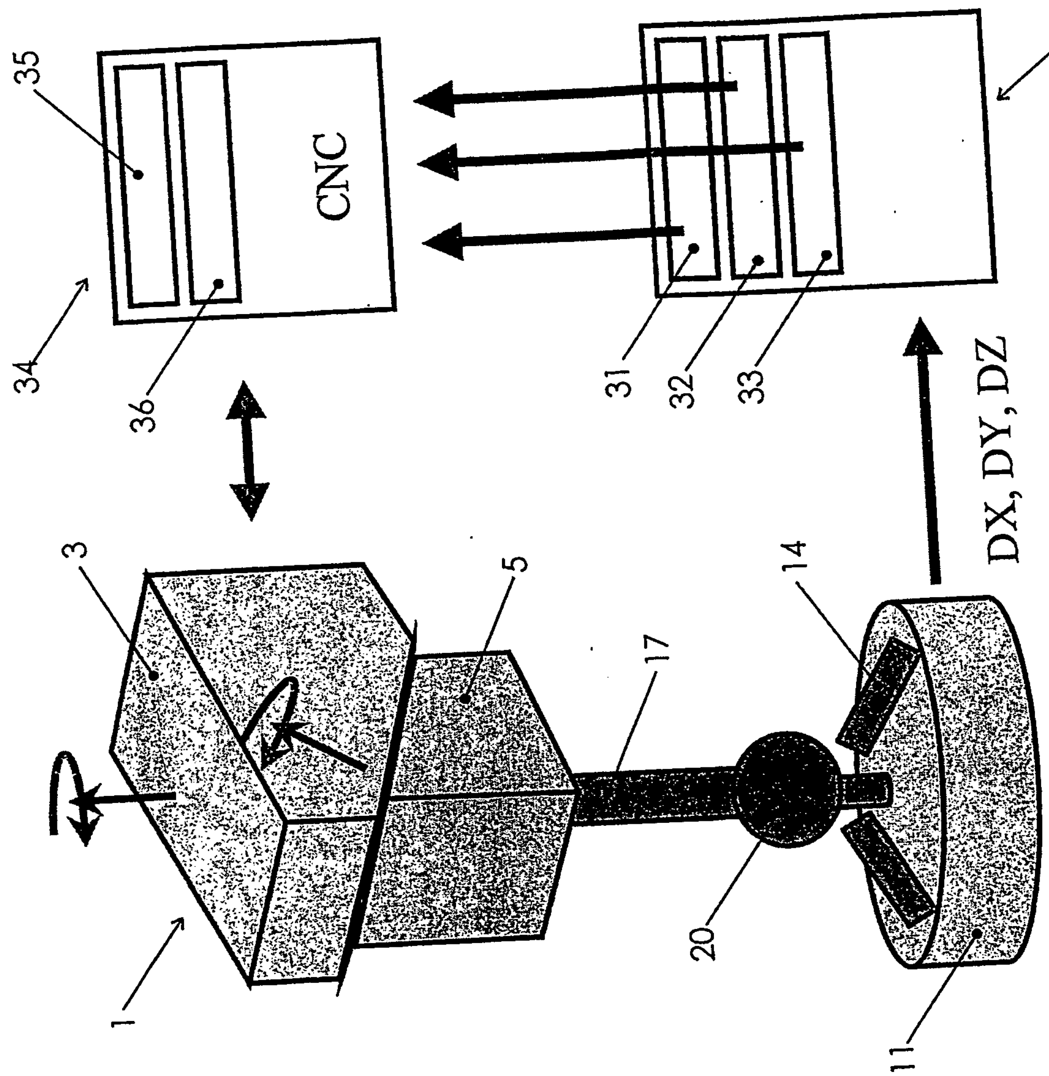

Fig. 6

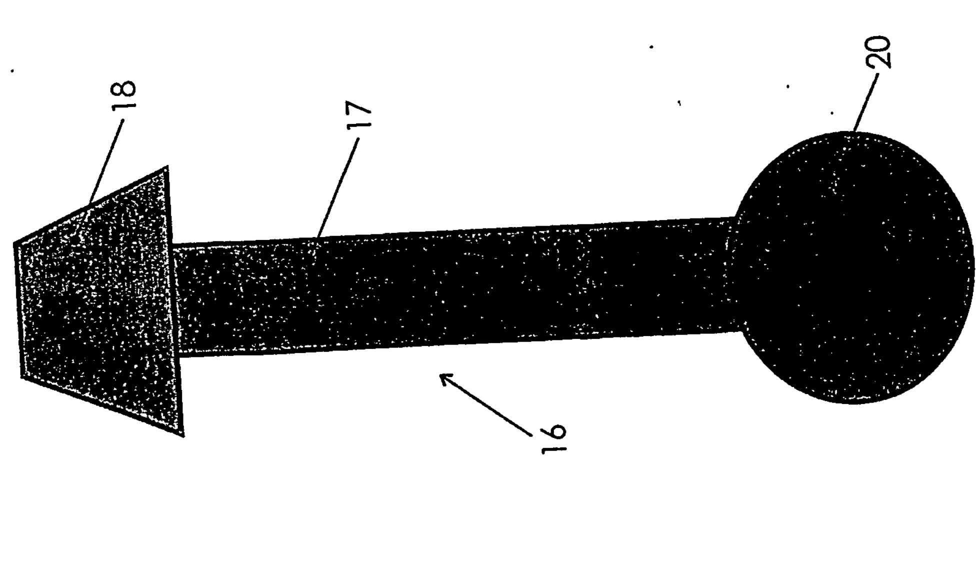

Fig. 3

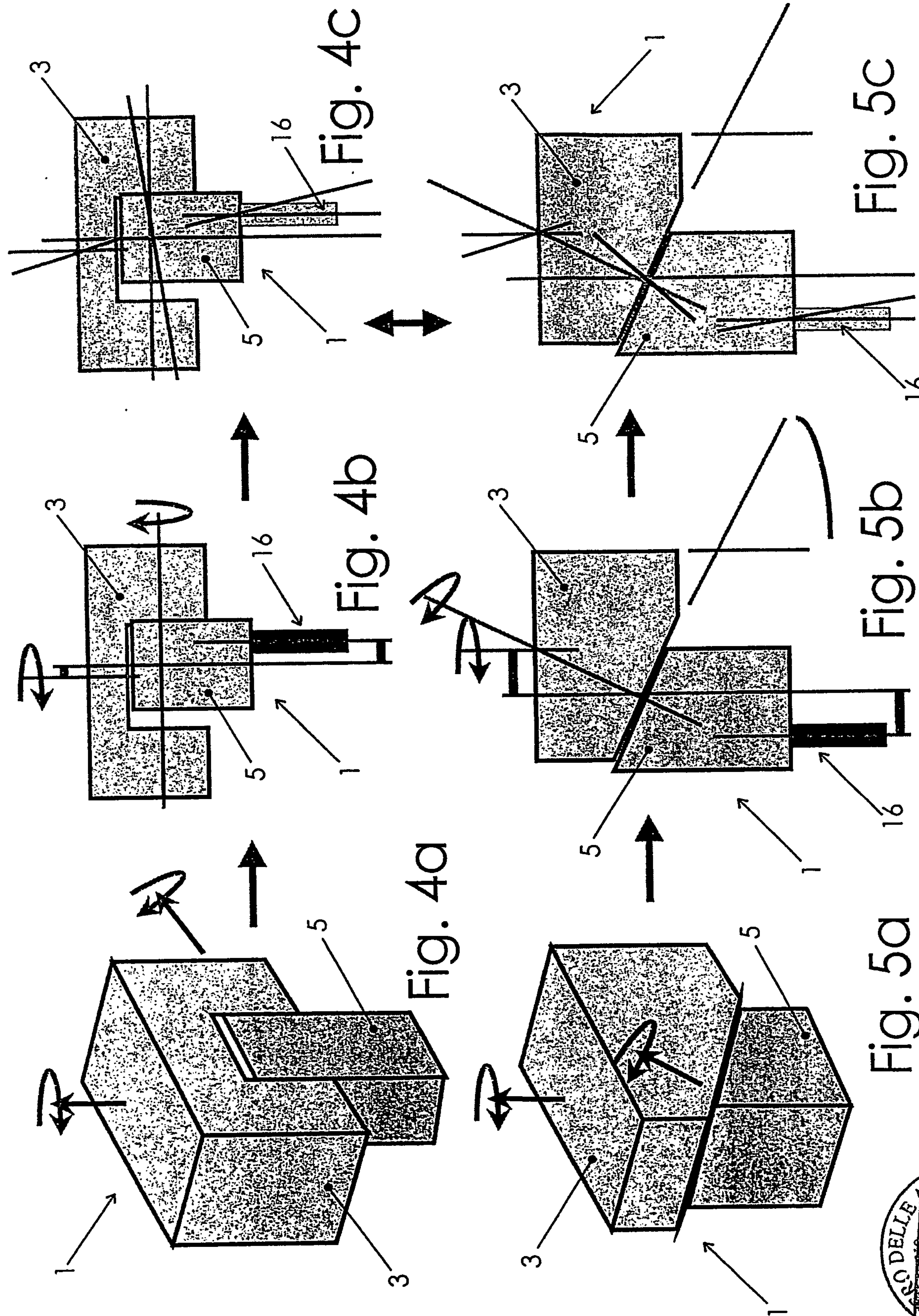

Fig. 4a Fig. 4b Fig. 4c

Fig. 5a Fig. 5b Fig. 5c

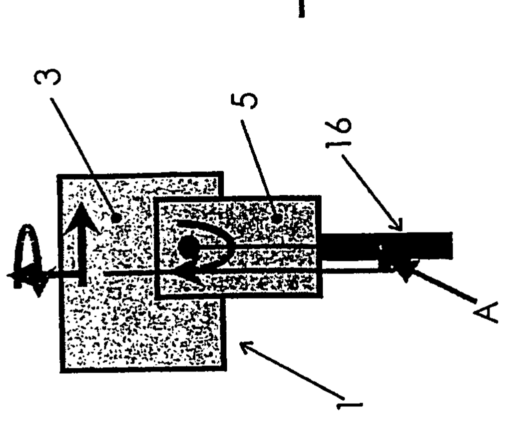

Fig. 7a

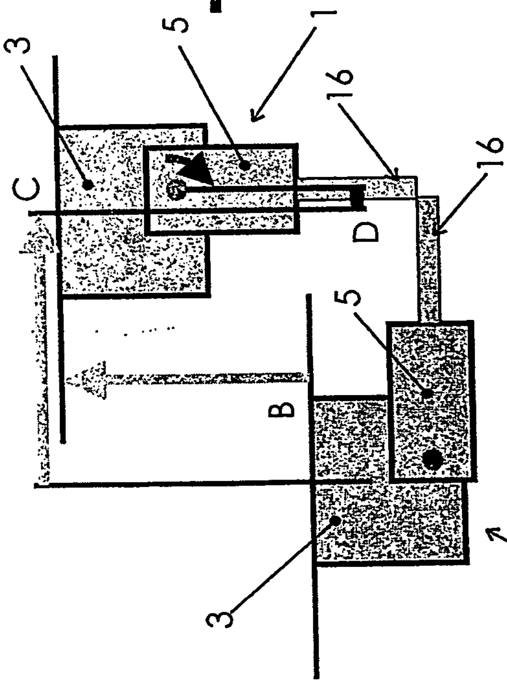

Fig. 7b

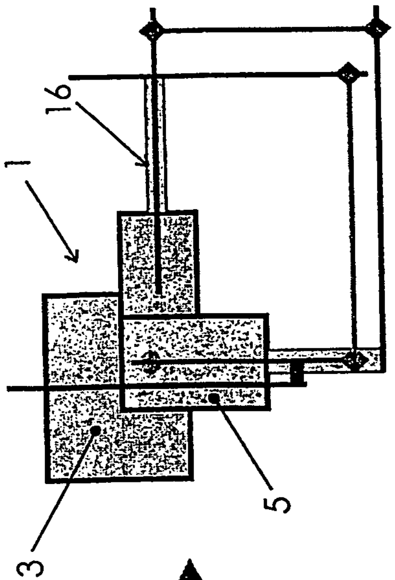

Fig. 7c

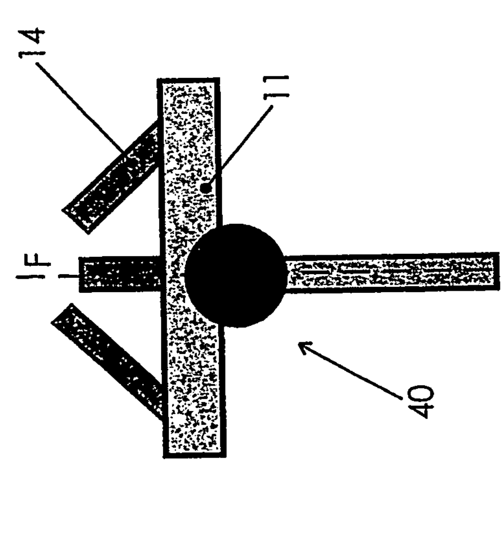

Fig. 8a

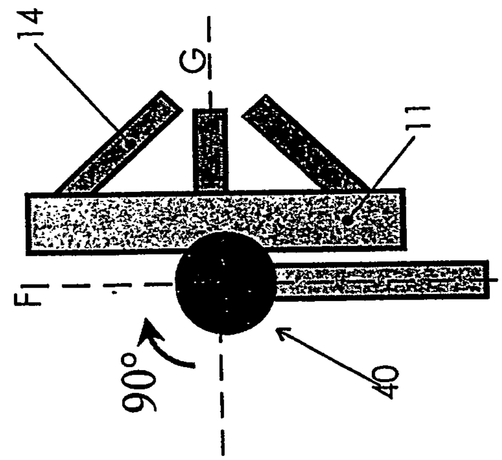

Fig. 8b

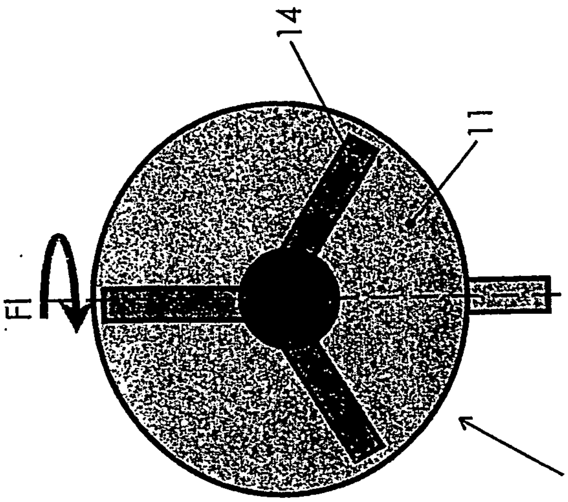

Fig. 8c

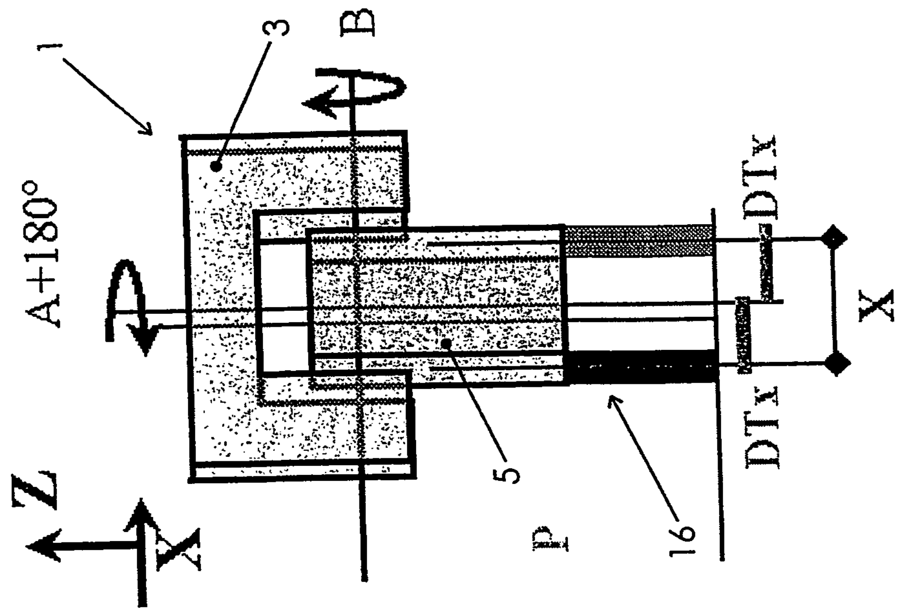

Fig. 10

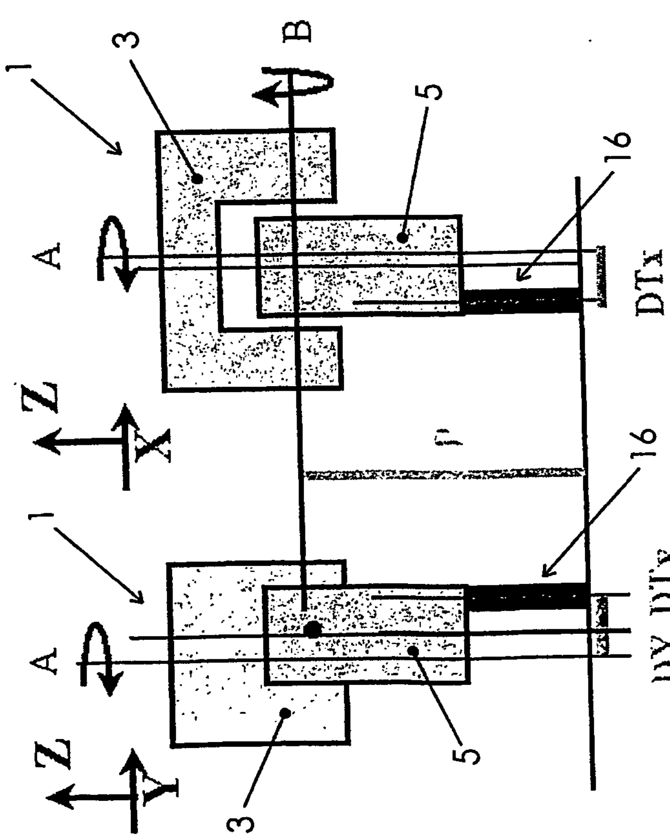

Fig. 9

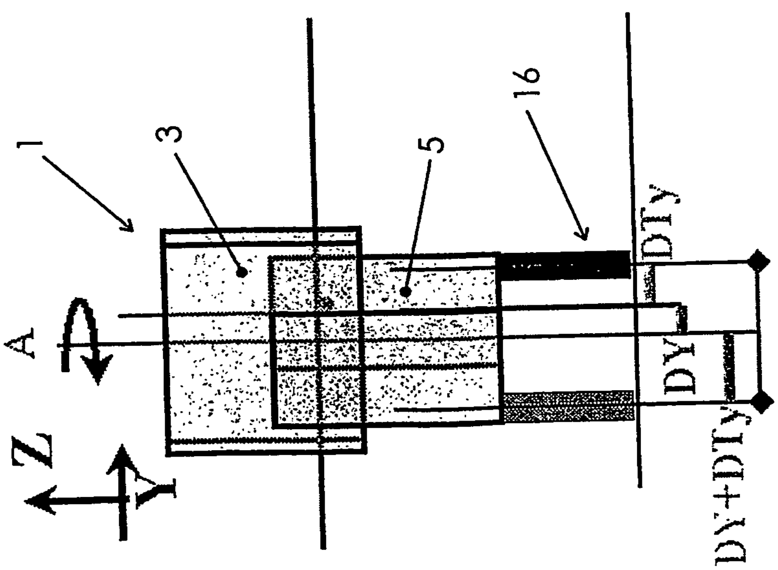

Fig. 11

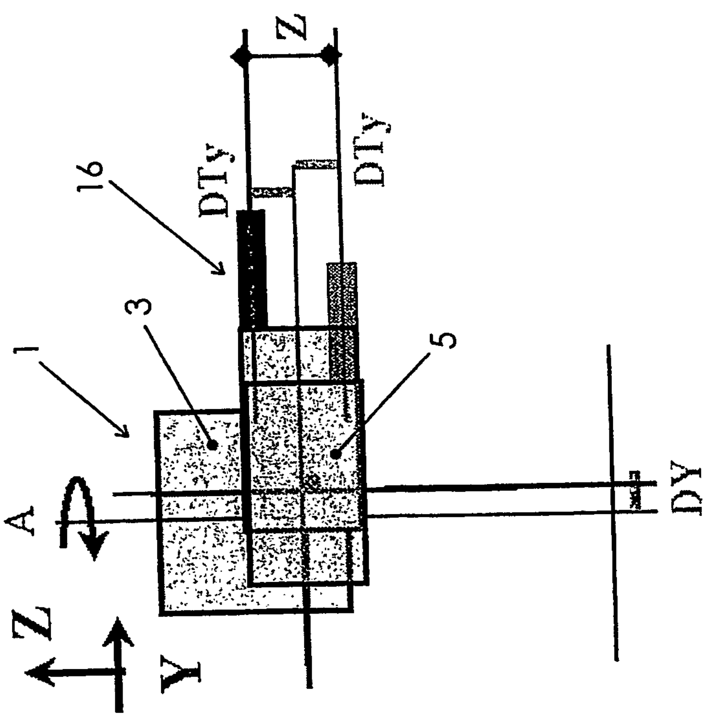

Fig. 12

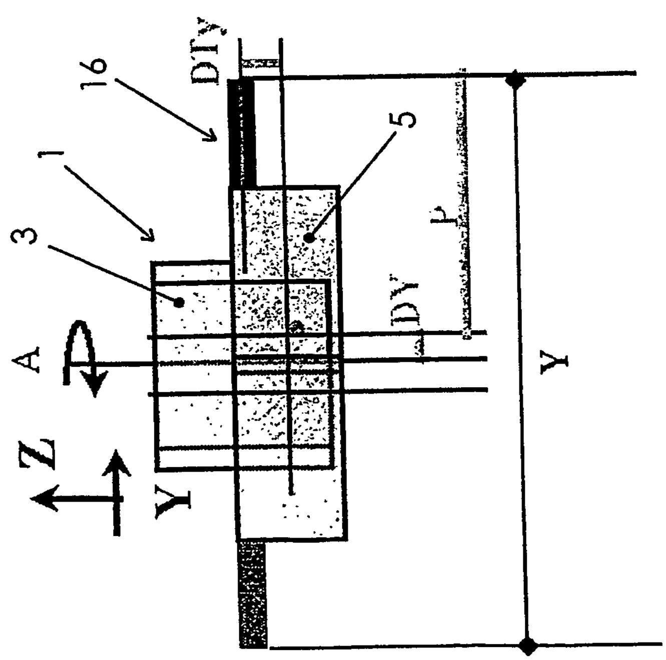

Fig. 13

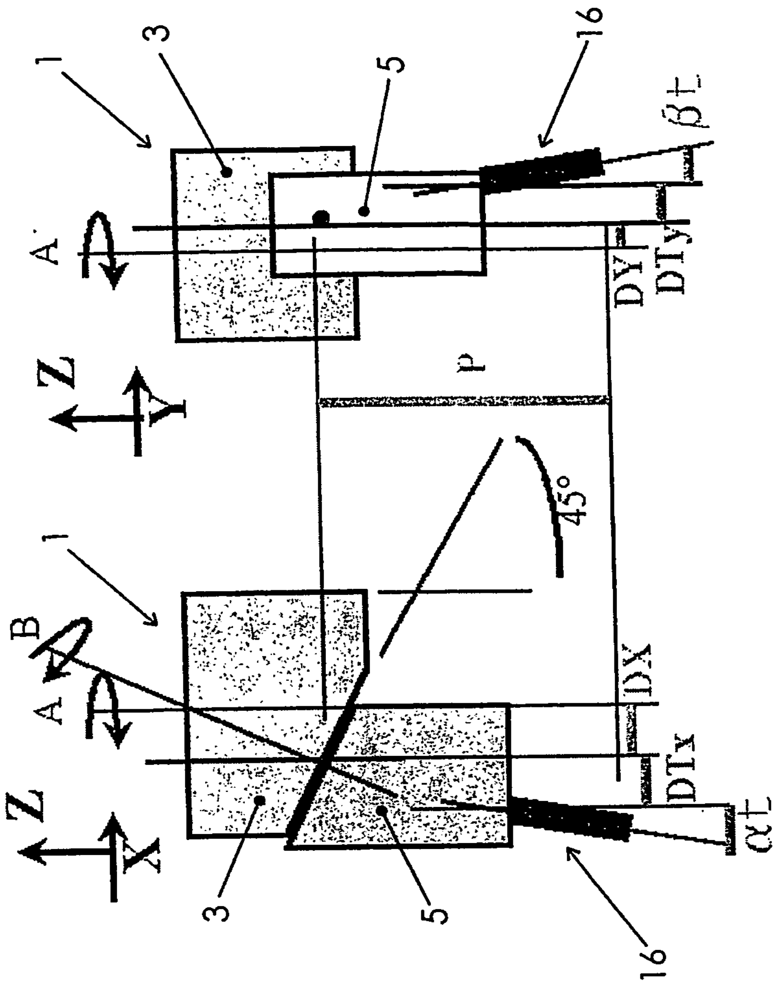

Fig. 14a

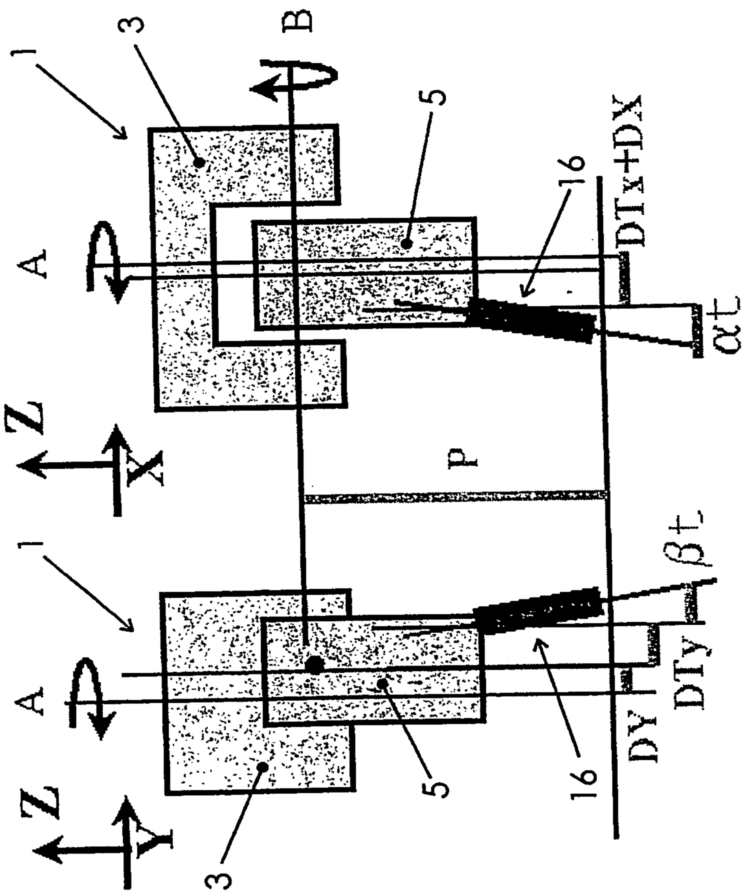

Fig. 14b

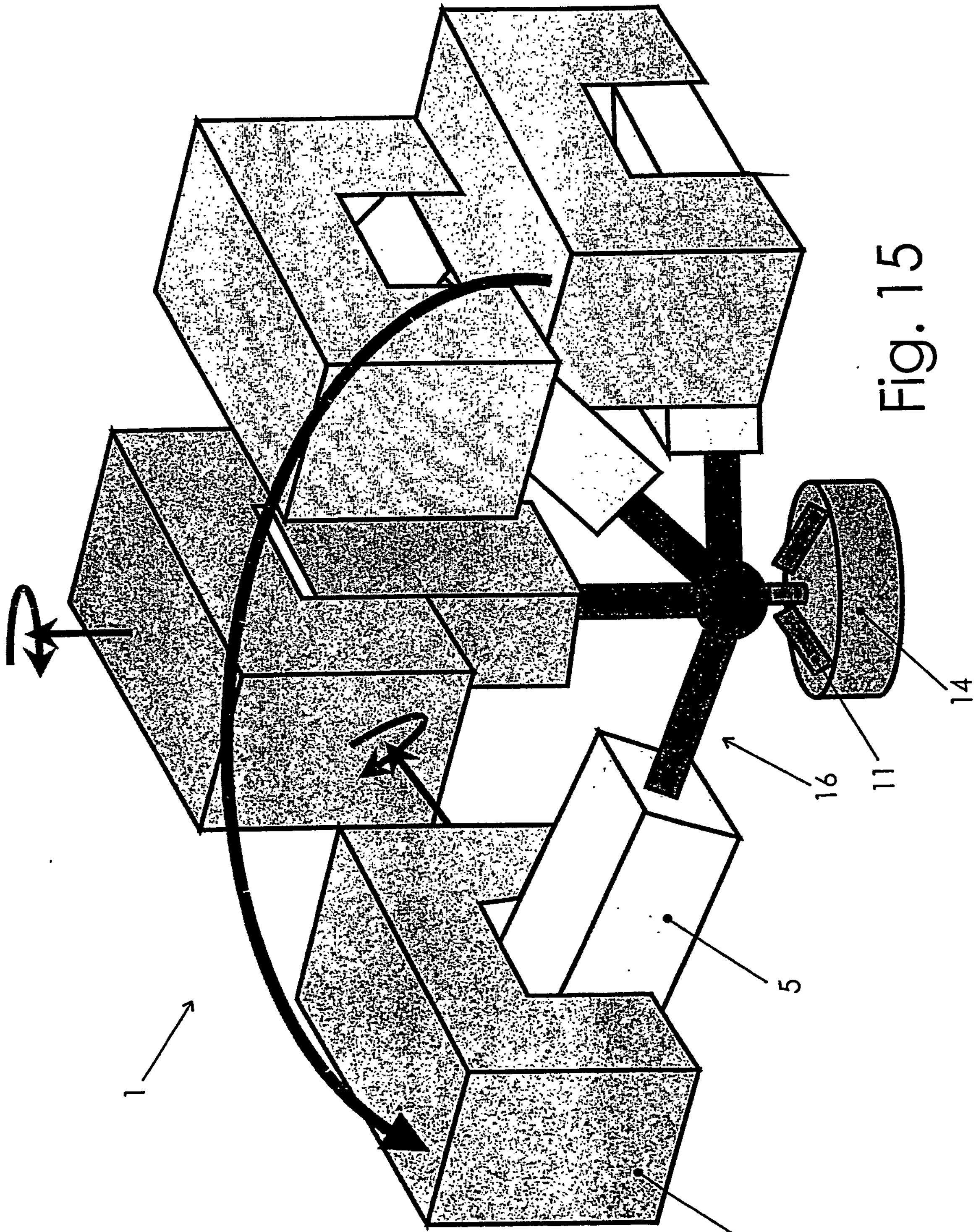

Fig. 15

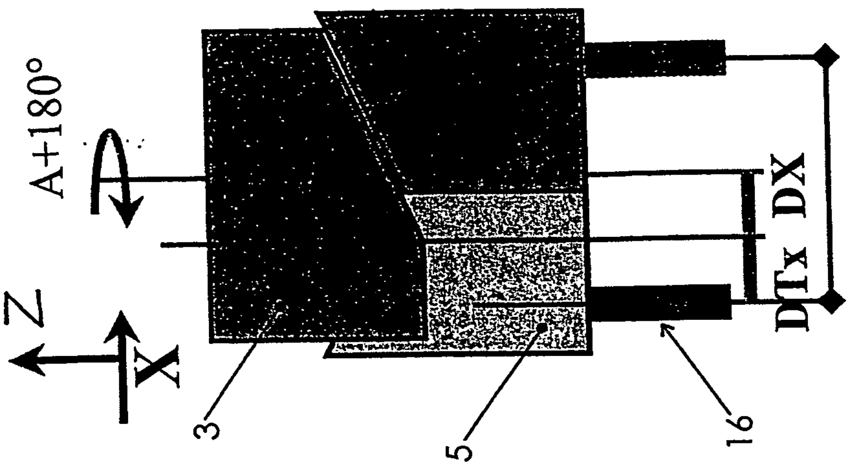

Fig. 17

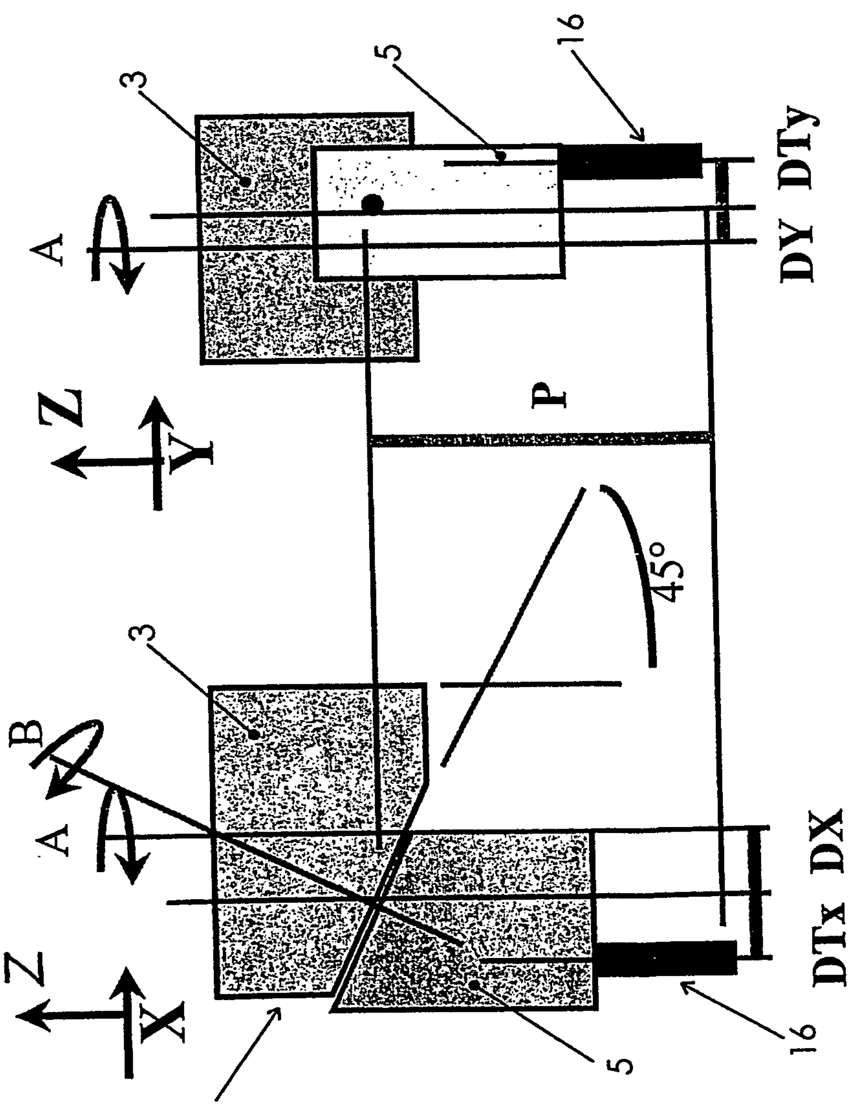

Fig. 16

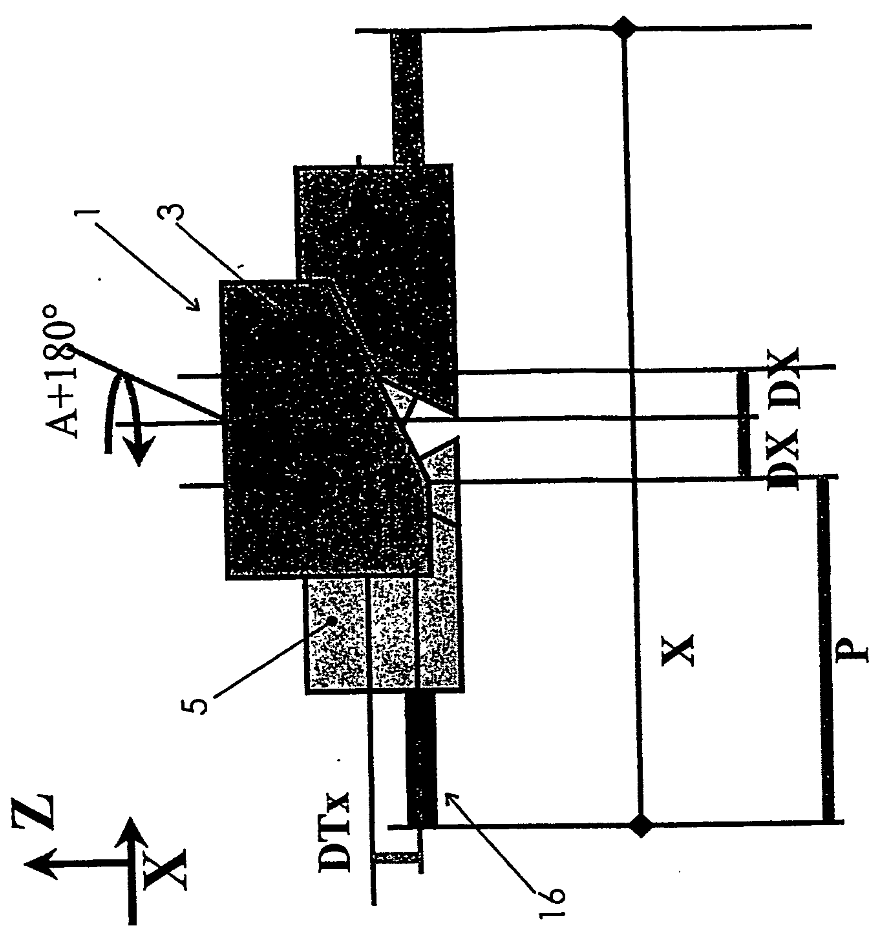

Fig. 19

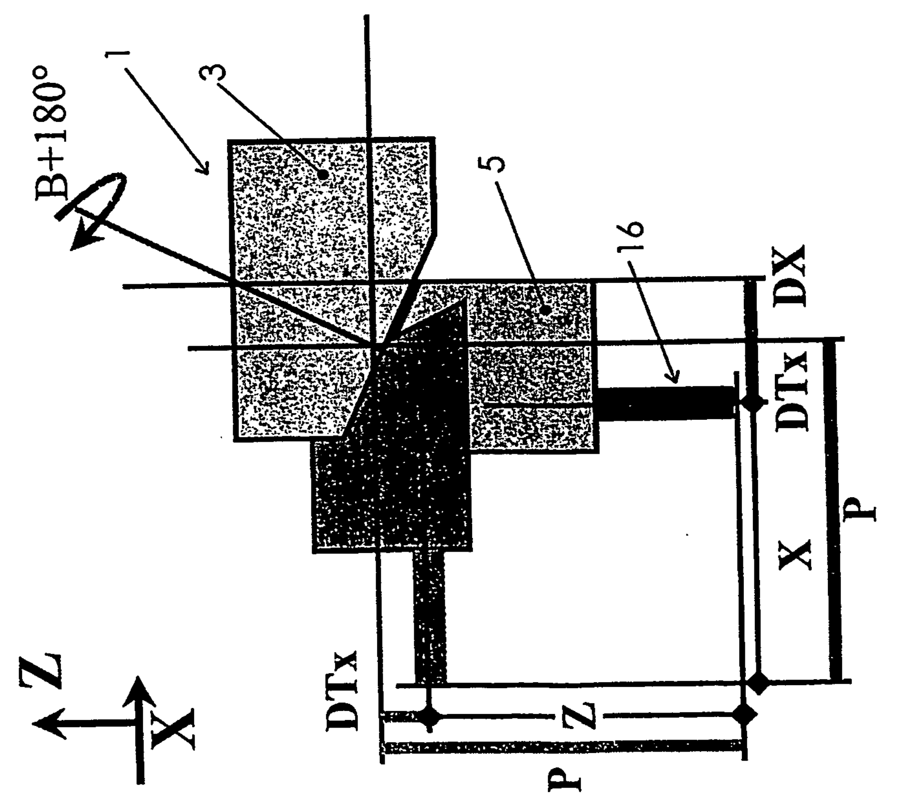

Fig. 18

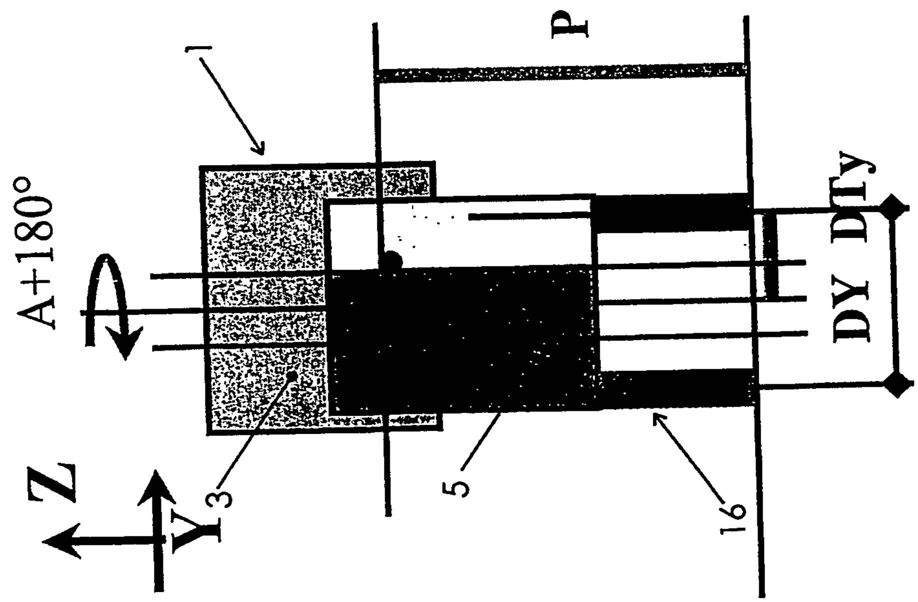

Fig. 20

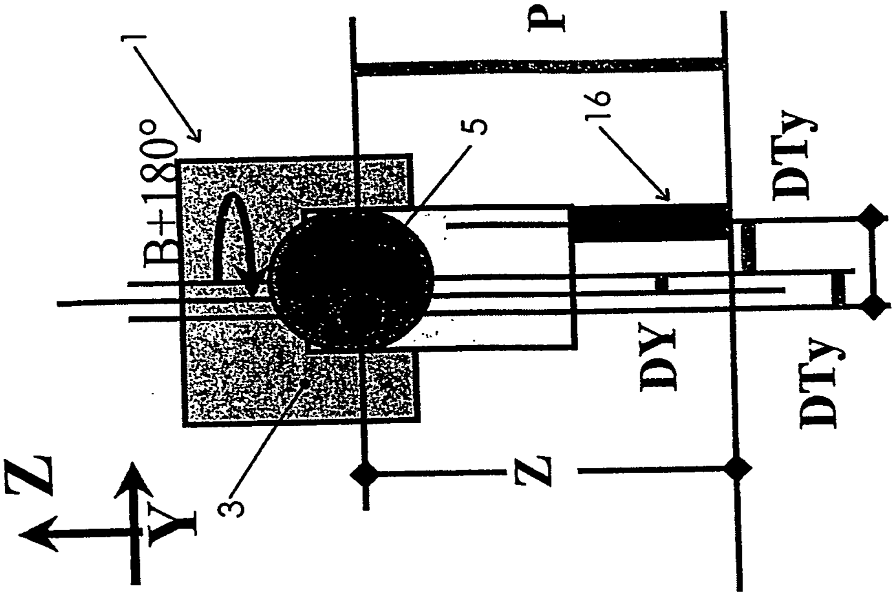

Fig. 21

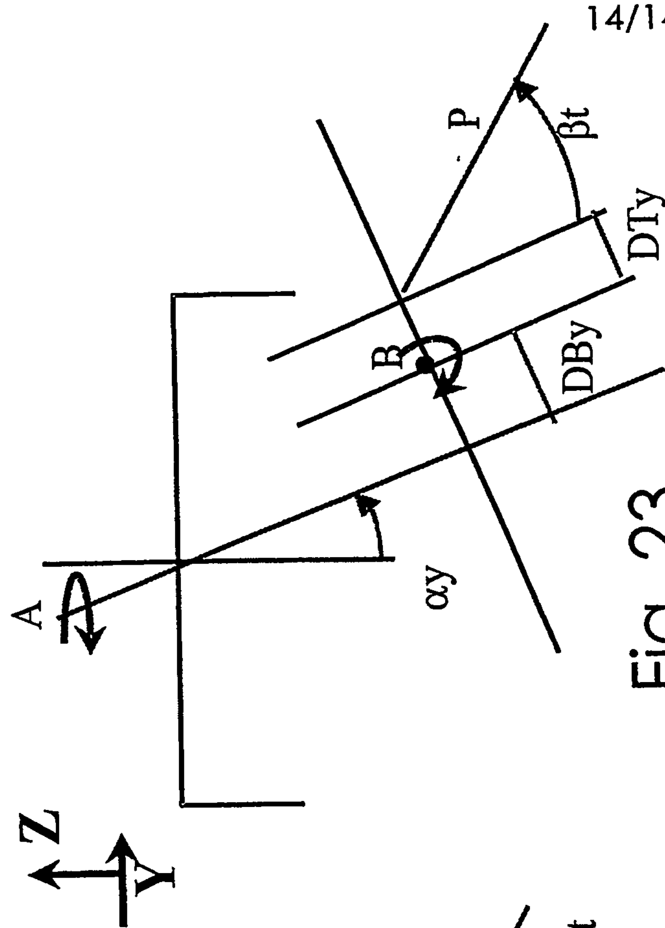

Fig. 23

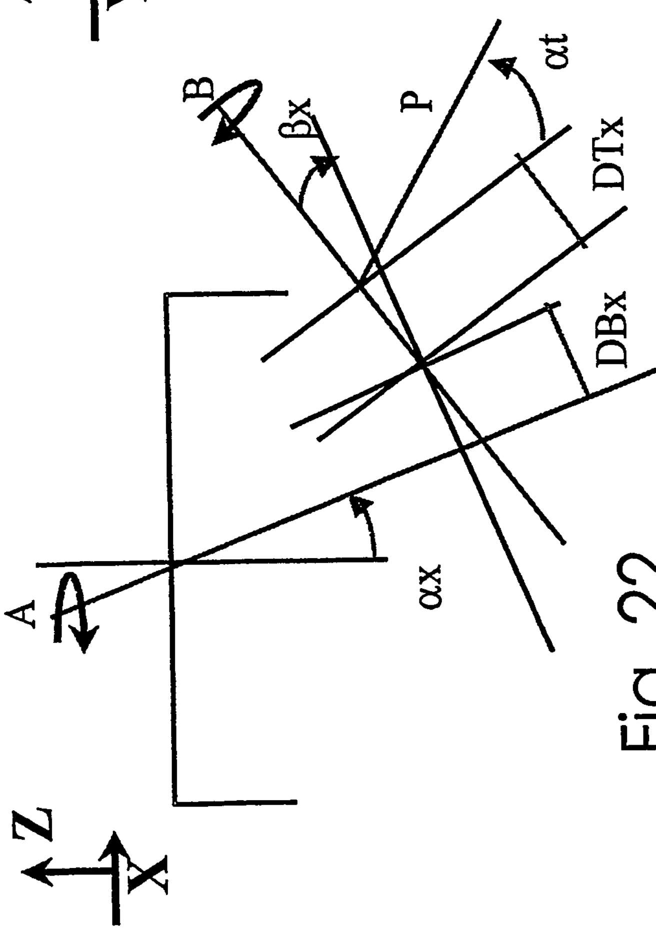

Fig. 22

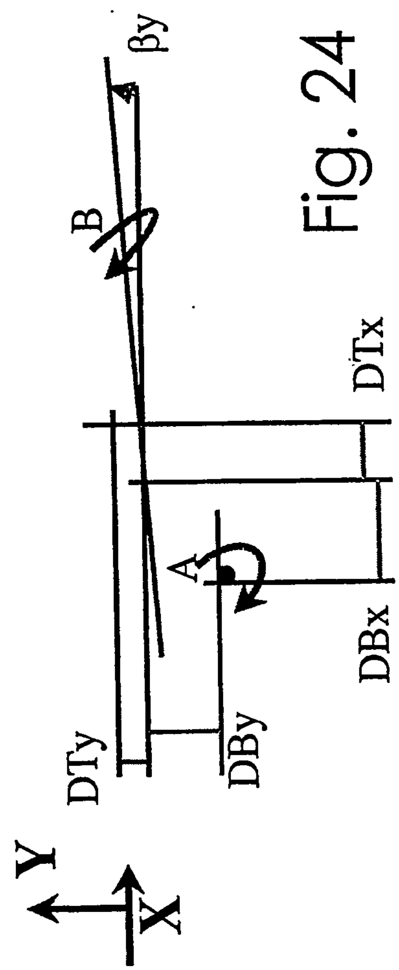

Fig. 24